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A vulnerability framework to protect coastal social ecological systems[1]

Timothy G. O'Higgins and Barry O'Dwyer

Abstract: Due to a long and beneficial legacy, human settlement and development is particularly concentrated in coastal zones and this concentration is expected to continue and increase in the future. Coastal dwelling, however, also entails risks from both anthropogenic and natural hazards and interactions between these. A spatially explicit ecosystem services framework combined with a vulnerability framework is used to explore human relations with the coast and to assess current and future capacities to ensure benefits of coastal migration and to address the risks that these areas pose. The spatial characteristics of some fundamental benefits — transport and settlement, fisheries and waste assimilation — of coastal dwelling and their associated environmental costs are first analysed using modern and historical examples. A variety of spatial characteristics describing human use patterns are then identified. On this basis, the implications of the variety of spatial scales in benefits and costs for effective governance are discussed with reference to historical and current marine and coastal management practice. Our analysis will attempt to demonstrate that incorporating ecosystem services in environmental management may provide a useful tool in the application of ecosystem-based management.

Key words: ecosystem services, adaptation.

Introduction

World population is expected to grow by a further 3 billion people over the next 80 years, equivalent to a city of approximately 1 million people every 10 days. Around 40% of the world's population resides on coastlines (Cohen et al. 1997) and coastal population densities are double those of inland areas (Small and Nicholls 2002). Coasts enable long-distance transport while also delimiting the extent of human settlement; coastal zones provide a ready source of food and their adjacent seas provide a means of assimilating the waste of human societies. Coasts have played a unique role in patterns of human settlement and development and most predicted population growth is projected to occur in these areas.

Yet coastal populations are uniquely at risk from natural and anthropogenic hazards and their interactions, being exposed not only to threats induced by climate change (Neumann et al. 2015), but also to unpredictable natural hazards. Coastal ecosystems are also uniquely threatened by increasing human activities and their associated environmental pressures (Halpern et al. 2008). Gradual processes, such as eutrophication, overfishing, and ocean

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acidification, may interact and can result in tipping points and multiple stable states (Duarte et al. 2009) as well as sudden social and ecological changes resulting in impacts on human welfare through degradation of ecosystem services (Worm et al. 2006). Major changes will be required of complex adaptive social–ecological systems in the coming decades, as human-induced environmental pressures continue to grow and begin to exceed planetary boundaries (Rockström et al. 2009), nowhere are these changes more urgent than at the coast.

To deal with the complex problems arising from the increasing pressures on global resources, a range of practical and theoretical frameworks have been devised. Holling (1973, p. 1) introduced the concept of ecological resilience recognising that in a "system profoundly affected by changes external to it and continually confronted by the unexpected, the constancy of behaviour becomes less important than the persistence of the relationships". Holling (1978) introduced the concept of adaptive management, which recognised that in the face of uncertainty over time, management of ecosystems required flexibility to include trial and error, or learning by doing. The concept of ecosystem management, with its origins in the conservation of US National Parks, identified that effective conservation of natural resources required consideration of ecosystem spatial scale beyond the human designation of park boundaries (Grumbine 1994). The popularisation of ecosystem services (Costanza et al. 1997; Millennium Ecosystem Assessment 2003) took an anthropocentric approach toward the conservation of nature, casting ecosystems as a source of benefits to human societies, an accounting approach quantifying in terms of human welfare a subset of the persistent relationships to which Holling referred. The concept of social–ecological systems recognised that human activities and ecological systems are coupled and effective management requires an holistic approach considering changes in both social and ecological components (Ostrom 2009).

All these ideas are combined within the modern conception of ecosystem-based management, which can be broadly defined as "an approach to management which integrates the connections between land air water and all living things including human beings and their institutions" (Mee et al. 2015, p. 3). Broadly, all these approaches are concerned with the effective management of changing environments maintaining human welfare while avoiding the depletion of natural resources. While there is considerable weight of theory to support more sustainable approaches to natural resource management, global assessments of practical progress to more sustainable development are depressingly consistent (e.g., IPBES 2019) and international policies for food production, which dominate the modern globe and generally fail to incorporate consideration of the multiple ecosystem services provided by nature, resulting in the gradual erosion of environmental quality (O'Higgins 2017; Rouillard et al. 2018). Based on our experiences of working with adaptation to climate change (Gray et al. 2013, 2016; DCCAE 2018*a*, 2018*b*) and application of ecosystem service concepts (O'Higgins et al. 2010; Jordan et al. 2012; O'Higgins and Gilbert 2014), the motivation behind this paper is to illustrate the simplicity and broad applicability of ecosystem service and adaptive management concepts (each component of ecosystem-based management) and to provide an integrated practical framework for future application.

Ecosystem services are the benefits gained by humans from nature (MEA 2003). Since the first controversial attempt to economically quantify the value of the world's ecosystem service (Costanza et al. 1997) the theory of ecosystem service science has developed greatly. There is now an accepted global Common International Classification of Ecosystems Services (CICES) and the formation of the International Panel on Biodiversity and Ecosystem Services (IPBES) in 2012 places ecosystem services concepts at the forefront of conservations science.

Despite the increasing global political focus on ecosystem services, practical application of these concepts remains limited; most large-scale analyses (e.g., Maes et al. 2015) have succeeded in treating only the ecosystem process, or supply-side, of ecosystem service analysis, neglecting the critical human demand-side, which can occur over different spatial scales. Mapping of ecosystem service potential supply (as in Maes et al. 2015) is akin to mapping ecosystems, but understanding how these services flow across the planet to provide benefits (i.e., understanding the human demand) and incorporating this understanding of the spatial relations between supply and demand into our management processes and institutions is the critical missing link between understanding that ecosystem services exist and ensuring that they are appropriately safeguarded (Cash et al. 2006).

Below we present an analytical framework incorporating social and ecological dimensions to explore coastal vulnerability. The framework is used to identify spatial characteristics of benefits, which are fundamental to human well-being and which make coasts attractive for settlement (food supply, waste assimilation, and transport), and their associated pressures, and to discuss the implications for vulnerability, management, and governance of coastal zone social–ecological systems. The first two are selected because feeding and excretion are two of the fundamental characteristics of living things, and therefore vital components of any human society. Globally, maritime transport (of food and other goods) is what enables coastal (and other) societies to develop beyond the limits of local natural resource constraints and as such is fundamental to any consideration of coastal development.

Materials and methods

The vulnerability framework

Rather than quantification or valuation of ecosystem services, this analysis draws on the work of Fisher et al. (2009) to examine the spatial characteristics of coastal ecosystem services. Fisher et al. (2009) presented a rudimentary classification of ecosystem services based on spatial relations of ecosystem service supply and demand in general. They recognised the binary distinction that production and benefits may occur in the same place ($P_{xy} = B_{xy}$), in situ, or that production and benefits may occur in different places ($P_{xy} \neq B_{xy}$), directional. They also recognised that supply may be spatially discrete but the benefits occur all around (omni-directional) implicitly recognising that P and B for some services exist on different scales. Building on the binary distinction between locations, in this classification (Fig. 1) spatial scale is explicitly included as a descriptor of supply and demand. In terms of spatial scale, there are three possibilities: scales may be matched, $P_z = B_z$, or scales may differ, $P_z > B_z$ or $P_z < B_z$. Figure 1 summarises the six possible unique combinations of location and scale relations with a suggested nomenclature. By substituting costs for benefits and pressures for production, the same typology can also be applied to examine the spatial characteristics of the environmental damage caused by human activities.

Environmental pressures to marine ecosystems may be either exogenous (unmanaged) or endogenous (managed) (Elliott 2011). For exogenous pressures, management cannot influence the occurrence of and exposure to an event and management may respond to the consequences of the pressure only (Elliott 2011). For endogenous pressures, which arise from human activities, management must respond to both the causes and the consequences of that pressure to address levels of exposure.

Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard. Hazards may be caused by perturbations (sudden shocks to the system) or by stressors (drivers), which cause stresses (or pressures). Figure 2 illustrates a scalable approach to examining coastal zone vulnerability incorporating exogenous and endogenous pressures as well as spatial characteristics of pressures

Fig. 1. Classification of ecosystem services based on location (*XY*) and scale (*z*) of production (*P*, grey circles) and delivery of benefits (*B*, white squares).

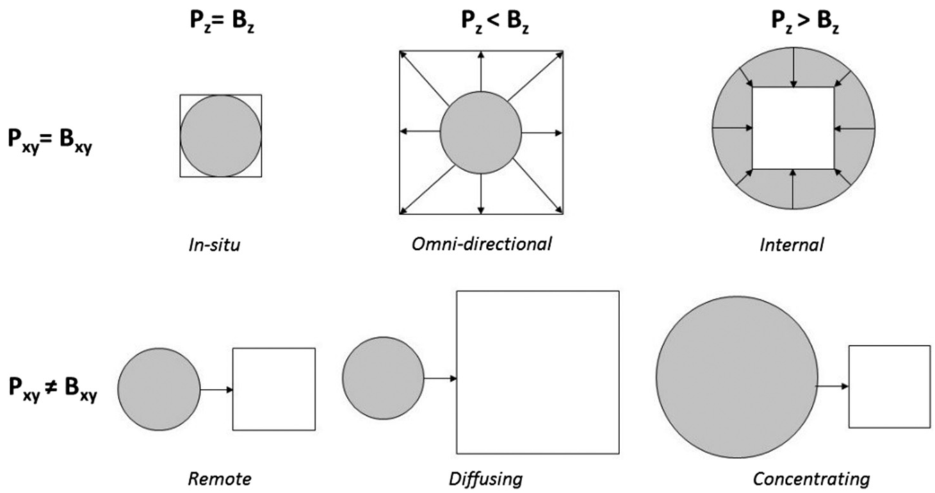
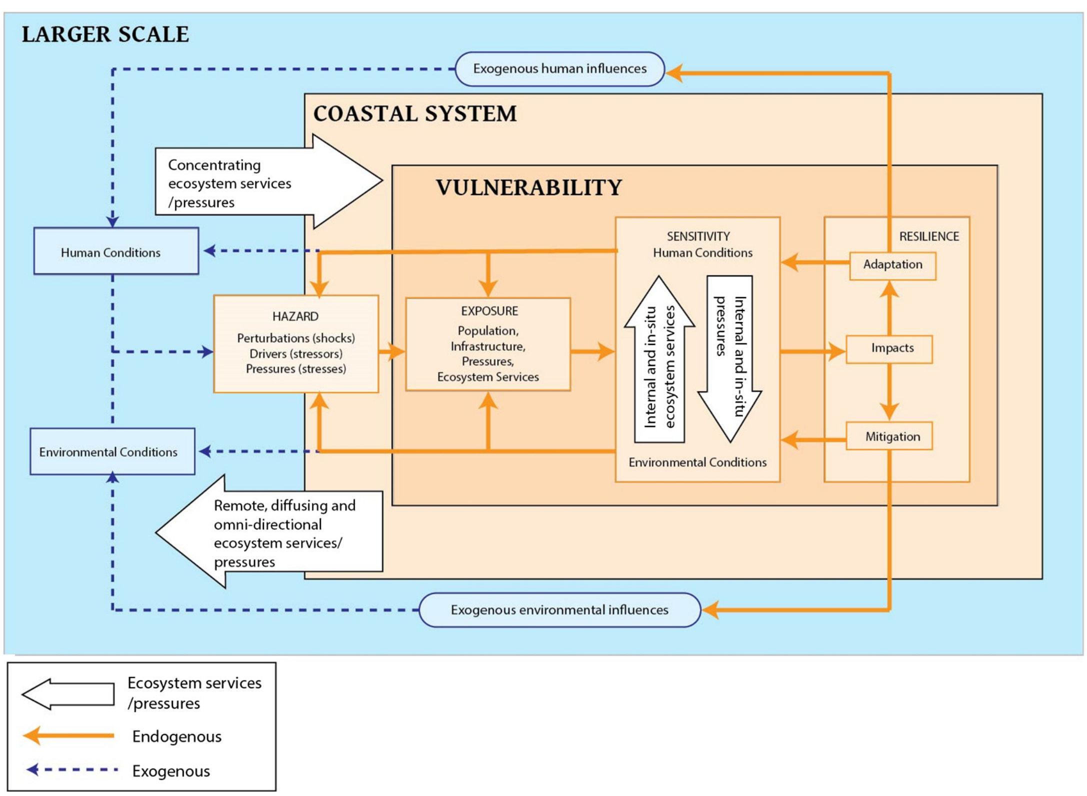


Fig. 2. Vulnerability framework and relationship to ecosystem services and pressures for coastal zones. Adapted from Turner et al. (2003).



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and ecosystem services. Explicit to this approach is the recognition of macro-forcing of the local environment, which can serve to interact and exacerbate endogenous pressures. For example, endogenous pressures resulting from deterioration in water quality will be exacerbated across scales by increases in global temperatures. In the following sections, the vulnerability framework presented above is used to examine selected valuable coastal activities and ecosystem services, fundamental to human settlement and development, as well as the hazards associated with their exploitation.

Results

Transport and settlement

The influence of history on coastal population patterns is undeniable. Ocean voyages and physical distance can explain temporal patterns in human settlement from cultural development of civilisations in New Zealand and Australia (Diamond 1997) to the successive discoveries of the American subcontinent. Though not quantifiable, there is no doubt that the physical characteristics of favourable ports and the consequences of these on the growth and local development of economic activity have been great. This is supported by the presence of many ancient cities on estuaries. Coasts are perimeters: the word port (derived from the Latin *porta* meaning door, gate or entrance) speaks of the importance of the coast in the connection of individual territories with the wider globe and the concept of the gateway city (Burghardt 1971). The transport patterns of the past have left a legacy in terms of human settlement, trade, and development, which are inextricably linked with current patterns. Shipping currently accounts for 90% of global trade.

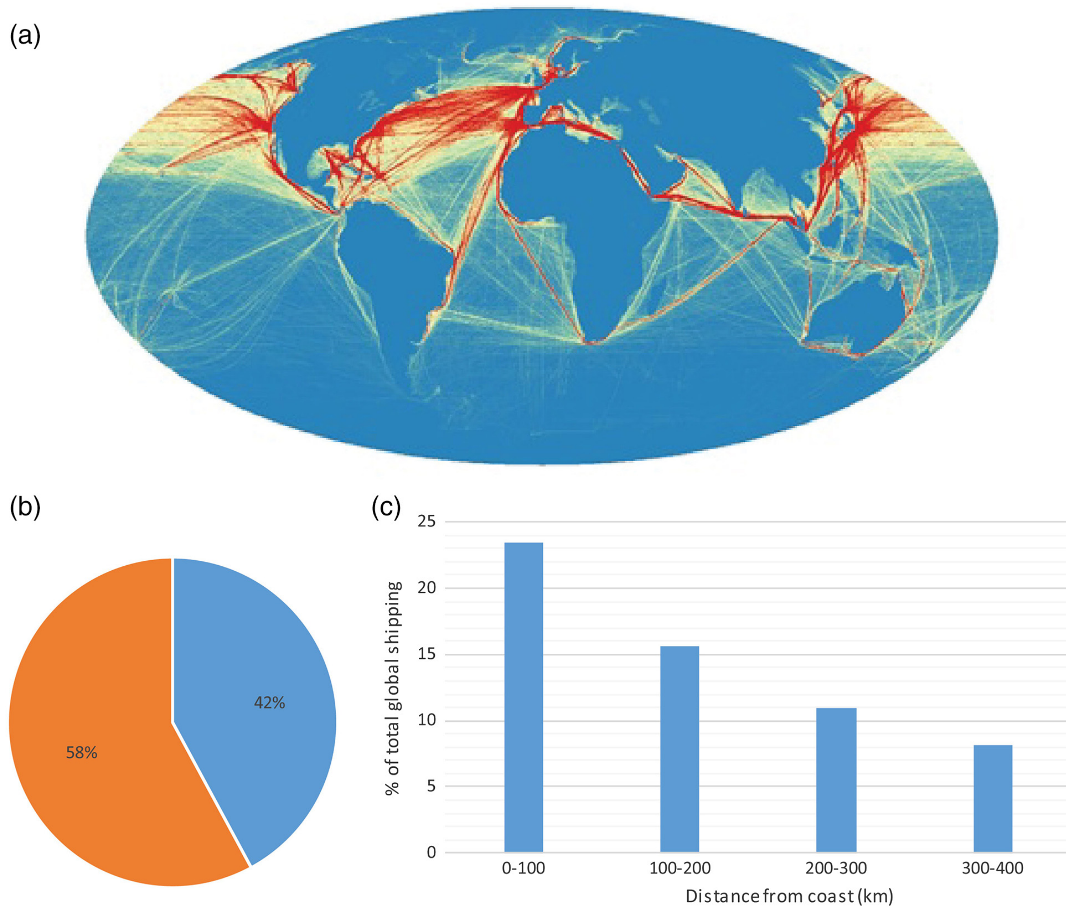
Figure 3*a* illustrates the spatial distribution of international shipping. A spatial analysis of this shipping activity (Figs. 3*b* and 3*c*) illustrates the degree of shipping activity within national Exclusive Economic Zones and at different distances from the coast. From a global perspective, the benefits of maritime transport have *concentrating* spatial properties, in that their production (in this case the passage from one location to another) occurs on larger spatial scales than the delivery of the benefits that occur, at smaller spatial scales, at ports and port-towns along the coast.

Concentrating properties are also associated with several of the environmental pressures (or costs) of maritime transport. Shipping emissions, catastrophic pollution events (such as oil spills), as well as the introduction of non-indigenous species have local health and environmental consequences concentrated in coastal areas. Atmospheric emissions of greenhouse gases (GHGs) from international shipping are also a major contributor to global GHG emissions with associated consequences for global climate, the spatial characteristics of these pressures are *omni-directional*, and their associated costs occur across every scale from local to global.

Food

Coastal marine environments are an abundant source of protein that is relatively easily accessed by coastal dwellers. The abundance of intertidal shellfish resources in prehistoric times and its exhaustion has been used to explain patterns in early human settlement and migration (Mannino and Thomas 2002). Intertidal habitats produce food in situ on scales larger than those of supply to individual beneficiaries small-scale harvesting can be characterised as *internal.* Depending on the particular choice of prey, supply of seafood (a provisioning ecosystem service) may have several different spatial characteristics. For example, rivers and estuaries act as conduits for important food sources: anadromous fish, such as salmon. Here, the provisioning service is *concentrating* because the service is produced remotely at large spatial scales but the benefits are experienced

Fig. 3. (*a*) Global maritime transport (from Halpern et al. 2008); (*b*) percentage within (orange) and outside (blue) Exclusive Economic Zones; and (*c*) percentage of global shipping traffic at different distances from the coast.

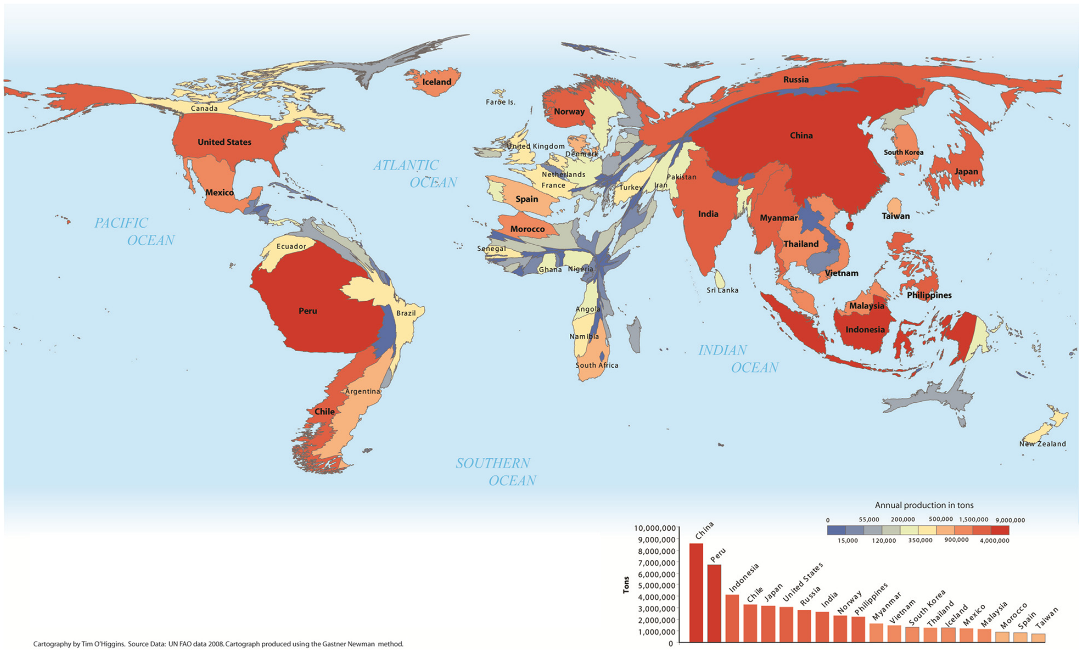


locally at small spatial scales. Such patterns of food supply can explain historical patterns of human settlement and development; for example, salmon populations in the Columbia River have supported human society for millennia (Campbell and Butler 2010).

Large-scale industrial fishing is a globalized endeavour. The spatial characteristics in this case differ from the local harvests in the examples above. The most productive global fishing grounds are generally upwelling regions or areas of productive coastal shelf (Pauly and Christensen 1995). For these large-scale commercial fisheries, the production of the ecosystem service is at discrete (and often distant) locations with a relatively small spatial scale while the benefits from the stocks are harvested from that location and experienced at the global scale, with *diffusing* spatial properties. Figure 4 illustrates the major global fish producers.

The provisioning services of seafood, and the economic activities these provisioning services support, may have drawn people to the coast but cannot explain the twofold difference in population density between coastal and inland areas. Fish protein in total makes up just less than 17% of animal protein, and about 6.5% of total protein, consumed by humans annually (FAO 2014).

Fig. 4. Cartogram showing FAO statistics of fisheries production with countries scaled by size of annual fish landings. Cartogram produced using the Gastner and Newman (2004) method in ArcGIS 10.2.



The greatest reported threat to marine species globally is overfishing (Harnik et al. 2012). The trend of "fishing down the food web" (Pauly et al. 1996) is widely acknowledged. The major economic costs of the exploitation of fisheries as a provisioning service are overfishing and depletion of stocks. Superimposed on these anthropogenic hazards are the many natural climatic cycles, similar to the well-known El Niño cycles, which can affect the productivity of fisheries and entire ecosystems across scales (Trenberth 1997). These are non-anthropogenic, unmanageable, and exogenous hazards.

Waste assimilation

Almost one-third of the world's population is without access to improved sanitation facilities (WHO-UNICEF 2015). For coastal regions, therefore (assuming 3 billion live by the coast), about 1 billion people rely entirely on the coastal ecosystems as their primary source of effluent disposal. Whilst wealthy nations have developed the infrastructure for treatment of sewage, for a very large minority, the truism that "the solution to pollution is dilution" is their only sanitation option. This service has *concentrating* spatial characteristics, recipients of the service may be relatively spatially discrete, situated in a coastal megacity, for example, while coastal ecosystems dilute and diffuse waste over large spatial scales and to different locations.

The service of waste assimilation for nutrients and organic matter by coastal ecosystems is not limited to human effluent. At the scale of river catchments, coasts often are the ultimate destination for nutrient wastes from agriculture, for example, the coastal areas of the Mississippi delta assimilate waste from around 40% of the US contiguous areas (Turner and Rabalais 1994). In this way, coastal regions supply benefits to the wider catchment. This is a *diffusing* service as the benefits occur on larger spatial scales (across whole catchments), but the assimilation occurs in a relatively small coastal area.

The capacity of coastal systems to assimilate waste is dependent on the specific physical and biological characteristics of that system (Cloern 1999); exceeding this capacity results in eutrophication, which entails costs in terms of ecosystem health and ecosystem service supply. There is anecdotal evidence for the occurrence of eutrophication in early coastal settlements. The biblical account of the first plague visited on the Egyptians bears many characteristics of an episode of severe eutrophication describing fish kills, foul smells, and water discolouration, all symptoms of eutrophication. "... [A]ll the water that was in the Nile was turned to blood. The fish that were in the Nile died, and the Nile became foul, so that the Egyptians could not drink water from the Nile" (Exodus: 7, 20–21, NASB).

Millennia later, by the mid-19th century, the capacity of the Thames estuary to assimilate the volumes of human effluent was exceeded and this loss of ecosystem services resulted in anther cost, "The Great Stench". The associated disease and public outrage at the problem prompted the modernisation of the London sewage system (Thompson 1991). At that time, the pressure and the cost were essentially collocated and led to an *internal* cost, this spatial property meant that the problem was *endogenous* and a technical solution was available, through construction of a new sewage system.

The problem of waste disposal in the U.K. has not gone away. While contemporary sewage treatment has removed the most severe public nuisance from the shores of the U.K., the modern problem of eutrophication in the North Sea is well documented (Los and Blaas 2010). Prevailing currents bring elevated nutrient concentrations from the U.K. to the coasts of northern Europe and coastal states on the shores of the North Sea have sought compensation. The spatial characteristic of this pressure and the costs in terms of eutrophication may be classified as *remote*, resulting in an exogenous unmanageable pressure for coastal states in the eastern North Sea from the waste assimilation benefits accruing to the U.K. to the west. The spatial characteristics of the pressures and associated costs have changed over the past century and a half as the U.K. population has continued to expand.

Similar problems can be observed around the world. Many large coastal settlements including several coastal megacities lack adequate infrastructure, such as urban wastewater treatment. Impacts of such large settlements, through pollution and wastewater, often have diffusing characteristics as the spatial scales of environmental degradation are larger than those of the source of the pressure. Wastewater-associated estuarine and coastal nutrient concentrations can have downstream effects leading, for example, to harmful algal blooms (green tides) along the entire neighbouring coastline of major settlements (Mee 2012); where the costs of eutrophication are borne outside the jurisdiction of their origins, management of effects may be exogenous. As with fisheries, there have been many attempts to develop management institutions to tackle cross-border nutrients.

Table 1 summarises the spatial characteristics of the ecosystem services and pressures identified in the examples above, highlighting the multiple spatial characteristics needing consideration to deliver effective coastal management.

Discussion

Arguments over the valuation of ecosystem services, combined with genuine methodological challenges in valuation of services, have restricted the practical application of ecosystem service concepts. A novel analytical framework has been used here to spatially characterise some of the most fundamental benefits provided by coasts. These include maritime transport as well as essential provisioning and regulating services, which relate to fundamental human biological processes of feeding and excretion. Our typology successfully provides a qualitative description of some of the spatial relations between ecological and social components of these benefits and the costs of their over-exploitation. The spatial characteristics of benefits supply and demand can be used to explain historic patterns in

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Table 1. Characteristics of costs, benefits, and hazards identified in the study.

Service or benefit			Location: Production or pressure (P_{xy})	Location: Benefit or cost (B_{xy})	Scale: Production or pressure (P_z)	Scale: Benefit or cost (B_z)	Spatial characteristic	Hazard type
Transport	Benefit	Transport of goods	Marine areas	Ports	Global	Local	Concentrating	—
	Hazard	Ship emissions (climate)	Ports	Global	Global	Local	Omni-directional	Exogenous
		Ship emissions (health)	Ports	Ports	Local	Local	Concentrating	Endogenous/exogenous
		Oil spills	Coastal areas	Coastal areas	—	—	Concentrating	Endogenous/exogenous
		Non indigenous species	Marine areas	Ports or coastal areas	Global	Local	Concentrating	Endogenous
Fishing	Benefit	Intertidal (fisheries)	Intertidal	Local	Local	Local	Internal	—
		Anadromous sp. (fisheries)	Open sea	Rivers or coasts	Ocean basin	Coastal	Concentrating	
		Global (fisheries)	Shelf or upwelling areas	Fishing ports	Global	Local	Diffusing	—
	Hazard	Overfishing limited mobility stocks	Intertidal or coastal	Fishing grounds	Local	Local	In situ	Endogenous
		Overfishing motile stocks	Ocean basin	Fishing ports	Ocean basin	Coastal	Concentrating	Exogenous
		El Nino	Pacific Ocean	Pacific fishing ports	Pacific Ocean basin	Pacific coastal communities	Internal	Exogenous
Waste assimilation	Benefit	Urban waste assimilation	Coastal marine	Coastal cities	—	—	Concentrating	—
		US agriculture waste assimilation	Mississippi Delta region	Continental US	Local	Continental	Diffusing	—
	Hazard	The Great Stench	London	London	Local	Local	Internal	Endogenous
		North Sea eutrophication	UK East coast	Northern Europe	Regional (N/Sea)	Regional (N/Sea)	Remote	Exogenous

coastal settlement and understand current patterns of ecological degradation. Our analysis reveals, and introduces a terminology to describe, a range of spatial relationships that entail costs and benefits to different groups of society, which occur across spatial scales. These relationships have profound consequences for the governance of ecosystems, and ecosystem services across scales.

For transport, the omni-directional global nature of the costs of GHG emissions is connected directly to global trade and economic growth. This omni-directional globalised problem requires a global solution. While high-level agreements, such as the Paris Agreement, adopted in December 2015 by the United Nations Framework Convention on Climate Change (UNFCCC 2015), have attempted to broker such solutions, the Intended Nationally Determined Contributions (INDCs) submitted by countries, which outline their post-2020 climate action, fall well short of the temperature objective of the Paris Agreement and imply a median warming of 2.6–3.1 °C by 2100 (Rogelj et al. 2016).

Similarly, the concentrating nature of the benefits from shipping result in concentration of vulnerability in these zones. This results in the concentration of pressures pollution and NIS in specific jurisdictions from vessels regulated under other jurisdictions. As with global climate, a globalised approach to regulation of shipping would also be required to address this problem. The International Maritime Organisation has just such a role in the regulation of environmental performance by shipping, but has been criticised for its lack of sanctions or proactive approach to improving environmental compliance (Campe 2009).

Hardin (1968) formalised the theory of the tragedy of the commons, describing the lack of incentive to manage fisheries sustainably under an open access regime. In terms of our vulnerability framework, open-access regimes lead to exogenous pressures, whereas regimes with restrictions to access may render these pressures endogenous. For fisheries where stocks have limited mobility and effort, targeting these stocks is in a specific jurisdiction, so the pressure and the cost are co-located or internal. For fisheries targeted at more mobile species or stocks, which straddle jurisdictional boundaries, some aspects of regulation may become exogenous. Institutions designed to render formerly exogenous fisheries endogenous, thereby avoiding the tragedy of the commons, have had various levels of application, including the International Whaling Commission (founded in 1946) and the North Atlantic Fisheries Organisation (founded in 1979) and the European Union's Common Fisheries Policy. While unravelling the success or failure of various fisheries management regimes is beyond the scope of this paper, the empirical work of Ostrom (1990), has uncovered a range of characteristics, or design principles, for such regimes, which can increase their success. One of these principles is to *build responsibility for governing the common resource in nested tiers form the lowest level up to the entire interconnected system*.

In the marine context, there have been many regional attempts to improve nutrient management and reduce eutrophication, and these have met with varying degrees of success (see Potts et al. 2012 for a comparison between the Helsinki and Black Sea Commissions), as well as concerted global scientific programmes to promote these approaches around the globe (Crossland et al. 2005).

When a particular hazard (ecological component) is exogenous to a particular jurisdiction (social system), that social system is more likely to experience harm due to exposure. Therefore, identifying and adapting the scale of organisation of social systems to account for and incorporate exogenous hazards has the potential to reduce vulnerability.

Historically, the seas were an open-access resource, and all hazards resulting from over-exploitation were exogenous. The Law of the Sea Convention expanded national jurisdictions to cover Exclusive Economic Zones, thereby rendering some hazards endogenous to the social system. However, delineation of maritime jurisdictional zones, which may make regulation of some environmental problems more manageable, does not account for the complex spatial properties of exogenous hazards or ecosystem service supply and demand.

The degradation of coastal environments globally gives testament to failures in coastal governance. A major challenge in future coastal management is to integrate more nuanced considerations of spatial scales. Ecosystem-based management is widely hailed by marine ecologists and conservationists as a model for coastal management. Such an approach "integrates the connections between land air water, all living things including human beings and their institutions" (Mee et al. 2015, p. 3).

We have demonstrated a methodology to identify the spatial relationships entailed in the flow of ecosystem services (benefits) and pressures (disbenefits). Flows of ecosystem services between spatial scales and jurisdictions set up interrelationships between different management areas (Paavola and Adger 2005). Incorporating these spatial interrelationships into management and institutional design will be critical to effective coastal management in the Anthropocene. These flows establish relationships or transactions between areas that are either beneficial or harmful and analysis of the flows can enable managers to identify where and with whom these transactions are occurring. Where these spatial relationships are remote, diffusing or concentrating, the lowest level (Ostrom 2009) for resource management is geographically distributed and requires polycentric governance (Ostrom 2010). The first step in establishing such governance is recognising where and with whom the transactions caused by these flows exist.

Conclusions

The risk framework illustrated here provides a promising basis for integrating the connections between social and ecological systems. However, while the examples above illustrate the different classes of scale relations between supply and demand of service and pressure and provide the first rudimentary application of the framework, more formal analysis and testing is required for operationalisation. The scales frame of reference considered above changed between each case, for example, from local intertidal to global fisheries. Practical coastal zone management applications will require more thorough consideration of how scales of supply and demand articulate with institutional boundaries, focusing on exogenous and endogenous supply and demand relative to fixed scales of management (O'Higgins et al. 2014). O'Higgins et al. (2019), for example, combined a similar classification with considerations of economic properties of ecosystem services to analyse the supply and demand relations for ecosystem services across jurisdictions. The potential to combine such approaches with the emerging methodologies for the analysis of environmental risk (e.g., Borgwardt et al. 2019) offers another avenue for further integrating the connections between social and ecological systems into the process of ecosystem-based management to enable the identification of common problems and to enable development of communities of practice based on commonly shared resources of connecting regions through flows of disbenefits. The ability to harness the power of the internet, big data and social media, and spatial data in developing, promoting, and informing such developments is as yet in its inception but represents a promising area for targeted research.

The vulnerability framework presented here incorporates the concept of resilience and the feedback between adaptation and mitigation measures on pressures and ecosystem services, both internal and external to a particular system; however, operational guidance and standardised methodologies (e.g., DCCAE 2018*a*, 2018*b*) provide a more practical tool to guide adaptation and mitigation measures. Here we have developed and applied a framework to illustrate the complexity introduced by scale in the management of coastal zones and to illustrate how spatial characteristics of benefits that have been fundamental to human development in coastal zones are also those that present challenges to effective coastal management. Coastal social–ecological systems face major challenges in the coming decades, but these challenges are not new. Understanding the fundamental properties and patterns in relations of environmental costs and human benefit in coastal zones may allow coastal mangers to learn from the past as they develop new approaches to managing social ecological systems for the future.

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